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ANALYSIS OF STRUCTURAL TRANSFORMATIONS OCCURRING DURING THERMAL HARDENING OF BUILDING REINFORCING STEEL PRODUCED AT BAKU STEEL COMPANY LLC

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For the production of building reinforcing steel, special charge components were used, consisting of steel waste, cast iron shavings and about 20 % of NVG pellets. Steel was smelted in a 60-ton electric arc furnace. The pouring of liquid steel was carried out on a continuous casting machine.

Heat treatment was carried out immediately after the rolling operation to improve the physical and mechanical properties of the construction reinforcing steels melted in the electric arc furnace from the charge material using metal waste. It is recommended that these steels be made of low-carbon (C≤0.25 %) and low-alloy steels in order to have a sufficiently high technology and good weldability. However, in order to meet the requirements of construction standards, these steels must have high structural integrity and physical and mechanical properties.

It was found that these requirements can be solved only by heat treatment immediately after the rolling operation of the armature. In this case, the effect can be obtained by reinforcing heat treatment of the fittings by hardening due to the rolling temperature. Therefore, in order to further improve the properties during thermomechanical treatment (TMT), the hardening was carried out directly (immediately) after the deformation in the roll.

Immediately after the spread, the physical and mechanical properties, as well as the fluidity and strength properties of the construction low-carbon reinforcement steels met the requirements of the standard by conducting HTMT. Increased strength and technological properties of reinforcing steel are achieved after hardening by dispersion hardening at high-temperature tempering, which is carried out at a temperature of more than 580 °C

Keywords: construction reinforcing steel, thermomechanical reinforcement, rolling, tabulation, physical and mechanical properties, microstructure

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1. Introduction

Reinforcing steels are used in various building structures that operate in difficult conditions: under the influence of high loads, earthquakes, corrosion, etc. Therefore, improving the quality of reinforcing steels is always an urgent problem due to the constant tightening of requirements for them. In this direction, to improve the quality of reinforcing steels, there are various approaches, among which steel alloying and heat treatment of reinforcing blanks are of dominating importance. Due to the fact that many plants smelt reinforcing steel from metal waste, which already contains certain alloying elements in its composition, however, their amount in the waste is not constant. Therefore, at present, the main vector of research is aimed at choosing the methods and modes of heat treatment of reinforcing blanks. Among the methods of heat treatment, thermomechanical treatment plays a dominant role. Here the difficulty lies in how to choose the optimal modes of thermal hardening of reinforcing steel, which would combine high strength properties and weldability of the material.

Therefore, improving the structure and properties of reinforcing steels smelted from metal waste by thermomechanical treatment is relevant and requires new approaches in this direction. For example, a change in the dislocation mechanism of hardening due to precipitation hardening of the structure of reinforcing steel requires new high-tech research.

2. Literature review and problem statement

Reinforcing construction steels must have good technological and welding ability. Typically, all building structures are obtained by welding, and therefore the ability to weld is considered a key property of building steels. From this point of view, construction structures are made of low-carbon ($C \leq 0.25$ %) and low-alloy steels [1, 2].

However, the above approaches in [1, 2] for the production of reinforcing steels and increasing their properties are based only on reducing the content of carbon to ensure good weldability and only on the principle of low alloying, which does not provide high strength of reinforcements that meet European standards. In [3, 4], it is recommended to reduce the amount of carbon in steel to 0.17÷0.20 %. This amount of carbon in steel ensures its good weldability, but steel becomes more ductile and therefore it cannot be significantly strengthened by thermomechanical treatment methods.

At the same time, a radical way to increase the strength of reinforcement is steel alloying [5, 6]. The doping effect is manifested in the crushing of the grains of the structure, the formation of solid solutions followed by dispersion hardening during thermomechanical treatment. Their complex effect leads to the formation of a certain finely reinforced structure, manifested in the size of iron atoms and the alloying element. However, alloying reinforcing steel is not a rational option for improving the bearing capacity, since it increases the cost of reinforcement and reduces its competitiveness in the world market.

At the same time, the works [7, 8] indicate that as a result of alloying, the grain boundaries have a different character compared to non-alloy steel, so its structure becomes more vulnerable to welding and operation. For example, in alloy steels with a ferritic-perlite structure, solidification occurs due to the crushing of grains as a result of separation into large-angle boundaries. Along with this, the mechanism of reinforcing the structure of steel through particles of the second phase of the alloying element (or elements) is important for structural steels that are not amenable to welding. Consequently, this approach of hardening steel is not acceptable for building fittings.

Based on this, it is necessary to find solutions that can improve the strength, and consequently the bearing capacity of reinforcing steel, while ensuring its good weldability. One of these solutions may be the use of low-carbon low-alloy steel with the subsequent improvement of its structure using high-temperature thermomechanical treatment, i.e. hot rolling with subsequent heat treatment. The final structure of such steel depends on the nature, size, hardness, distribution, and other factors of the second phase. For example, the structure of low-carbon low-alloy steel can be significantly strengthened during thermomechanical treatment due to dispersion hardening, i.e. the formation of only a dispersed second phase against the background of a relatively plastic matrix.

It should be noted that dispersion hardening during thermomechanical treatment can lead to the hardening of steel and, on the contrary, to deterioration in its weldability. On the one hand, this will lead to the formation of microtriches and an increase in the hardness and fragility of the weld, and on the other, to the appearance of cold cracks during the operation of the reinforcement structure.

Therefore, it is necessary to maintain an optimal balance between the dispersed solid structure and weldability of steel in order to avoid the formation of a Widmanstett structure and stresses in the welding zone. Therefore, it is important to take these circumstances into account when choosing the chemical composition, steel smelting technology and thermomechanical treatment (rolling with subsequent heat treatment) of non-primary valve blanks and conduct new research in this direction.

All this allows us to assert that it is expedient to conduct a study devoted to establishing the relationship between the optimal composition of the charge for steel smelting and the modes of high-temperature thermomechanical treatment of blanks of building fittings, their structure and properties.

3. The aim and objectives of the study

The aim of the paper is to improve the structure and increase the strength, as well as the operational properties of low-carbon low-alloy reinforcing steel through the use of high-temperature thermomechanical hardening.

To achieve this aim, the following objectives are accomplished:

– to analyze the compositions and properties of reinforcing steels produced in Baku Steel Company LLC;

– to study the features of thermal hardening of reinforcing steels;

– to study the effect of thermal hardening on the strength properties of low-carbon low-alloy reinforcing steel;

– to study the relationship between deformation during thermomechanical hardening and structural transformations of reinforcing steel.

4. Materials and methods

Metal waste of various chemical compositions and sizes, ferroalloys, secondary aluminum, iron ore pellets and flux were used as the starting charge materials. Steel smelting was carried out in a 60-ton electric arc furnace with sour lining. After smelting in an arc furnace and out-of-furnace treatment in a ladle furnace installation, the chemical composition of the reinforcing steels corresponded to the data given in Table 1.

Table 1

Standard chemical composition and mechanical properties of fittings

No.	Standard	Brand	Chemical composition									Mechanical properties			
			C	Mn	Si	P	S	Cr	Ni	Cu	N_2	R_m	R_t	δ_5	Bending degree
1	GOST2016-34028	A400C	<0.22	<1.60	<0.90	0.05	0.045	<0.3	<0.3	<0.3	–	590	390	16	90°
		A500C	<0.22	<1.60	<0.90	0.05	0.045	<0.3	<0.3	<0.3	–	600	500	14	90°
2	GOST52544-2006	A500C	<0.22	<1.60	<0.90	0.05	0.05	–	–	0.5	–	600	500	14	90°
3	EN10080-2005	B500C	0.22	–	–	0.05	0.05	–	–	0.8	0.012	–	500	–	90°
4	ASTM615-60	615–60	0.19–0.32	1.2–1.6	1.2–1.6	<0.04	<0.04	–	–	–	–	615	420	7	90°

Note: The EN10080-2005 standard allows N_2 *max 120 ppm. The strength limit is 1.15–1.35* R_t

The study of the macrostructure of reinforcing steels was carried out on a NEOFOT-21 metallographic microscope before and after thermomechanical hardening. Hot rolling of continuously cast blanks on a special mill was carried out at a temperature of more than 1,250 °C.

As a result, high-temperature thermomechanical treatment took place, in which the density of dislocations in the austenite increased, and in the process of cooling, austenite turned into martensite, which provides thermal hardening of reinforcing steel. The release of this steel was carried out at a temperature of 580 °C. The mechanical properties, including tensile strength, yield strength, elongation and bending strain of reinforcing steel after thermomechanical treatment, have been determined by the test methods set out in the relevant international standards [9–12]. High-temperature thermomechanical treatment was carried out on reinforcing steel blanks obtained by continuous casting.

5. Results of studies of structural transformations during thermomechanical treatment of reinforcing steel

5. 1. Reinforcing steels produced by Baku Steel Company LLC

The main purpose of this work is to ensure the production of specimens with high reinforcement characteristics and good weldability properties on the basis of control of alloying additives leading to thermal reinforcement of the microstructure of rebar steels used in the construction industry.

Another way to increase the strength of structural reinforcing steels is a dispersed reinforcement mechanism. In this case, the increase in the fluidity limit of steel depends on the number, size, distribution nature of the dispersed particles and the distance between them.

All these reinforcing mechanisms of steel are carried out during rolling and thermomechanical treatment. Thermomechanical treatment (TMT) is a method of strengthening steel, which consists of a combination of plastic deformation in the case of austenite [13–15].

These steels are low-carbon, low-alloy and 605–60 low-alloy steels with grades A400C, A500C and B500C. Their chemical composition and mechanical properties are given in Table 1.

The cross-sectional areas of the fittings produced by Baku Steel Company LLC on profiles vary from 10 mm to 32 mm (Table 2). The properties of branded fittings vary significantly depending on the thermomechanical treatment modes. For example, A400 steel has a fluidity limit of 390–590 MPa and a strength limit of 590–750 MPa. In A500, A500C and At500 steels, these values are slightly higher than in A400 steels and are in the range of 500–700 and 600–800 MPa, respectively [15, 16], only in At1000 steel these values are much higher than in other steels and are $\sigma_{0,2}$=100, σ_b=1,250 MPa, respectively.

A comparative analysis of these indicators shows that the mechanical properties of fittings with the same chemical composition, but obtained in different technological modes, differ significantly from each other. Thus, the mechanical properties of thermomechanically processed reinforcing steels are much higher than in the desired A400 and A500 steel fittings.

As follows from the data in Tables 1, 2, a significant difference in the strength properties of reinforcing steels having the same chemical composition lies in the fact that in steels that have undergone thermomechanical treatment, structural transformations occur from deformed austenite. Twinning of austenite during high-temperature deformation increases its degree of metastability. This state of austenite leads to a significant change in the structure and the separation of dispersed phases during quenching, followed by high-temperature tempering of the steel.

Table 2

General geometrical and mechanical properties of fittings rolled in Baku Steel Company LLC

No.	Brand of steel	Standard	Permissible diameter on stamps, mm	Mechanical properties Cross-section				Carbon equivalent	Do not bend in the cold	Cross-section of profiles	Cross-section	Paqon meter		
				Limit	R_t	R_m	δ_5	Ce			Fn, mm^2	P_m, kq		
					N/mm^2		%	%			nom	min	nom	max
1	A400	GOST 34028-2016	10–32	min	390	590	14	30–50	180°	8	50.3	0.367	0.395	0.430
				max	590	750				10	78.5	0.579	0.617	0.647
2	A500	GOST 34028-2016	10–32	min	500	600	14	<50	180°	12	113.1	0.834	0.888	0.932
				max	700	800				14	154.4	1.137	1.210	1.270
3	At500	GOST 34028-2016	10–32	min	500	600	14	<50	90°	16	201.4	1.501	1.580	1.627
				max	700	800				18	254.8	1.900	2.000	2.060
4	A500C	GOST 52544-2006	10–32	min	500	600	14	<50	180°	20	314.6	2.347	2.470	2.544
				max	700	800				22	379.6	2.831	2.980	3.069
5	B500C	EN10080-2005	10–32	min	500	–	14	<50	180°	25	490.4	3.658	3.850	3.965
										28	615.3	4.589	4.830	4.975
6	At1000	GOST 34028-2016	10–32	max	1000	1250	7	–	45°	32	803.8	6.310	6.310	6.499

Note: 1. Up to 200 N/mm^2 is allowed to increase the R_m value for this class of fittings.
2. Cr and Ni in the armature A500C are regulated by not exceeding Ce≤50

5. 2. Features of thermal reinforcement of reinforcing steels

The sum of the spread of reinforcing steels and the subsequent immediate heat treatment can be called high-temperature thermomechanical treatment (HTMT). The purpose of high-temperature thermomechanical treatment is to obtain a non-recrystallized saturated solid solution with red-hot plastic deformation (rolling process) and high density deficiency (free dislocation and sub-grain boundary) immediately after annealing. After tabulation, high mechanical properties are formed as a result of stratification. Additional reinforcement during high-temperature thermomechanical treatment is provided at virtually constant plasticity values.

After high-temperature thermomechanical treatment, a heterogeneous structure is formed. Because this structure is not stable, if rapid cooling is not provided, a break occurs and, as a result, the properties are not achieved at the required level. Therefore, it is necessary to influence the crystallization process. In other words, landfills should not be allowed to go.

Thus, during high-temperature thermomechanical treatment, austenite is deformed in the thermally stable zone during the rolling process, then annealed, and after annealing is subjected to high stratification.

Requirements for the strength properties of reinforcing steels in construction, including increasing their strength and improving cold resistance, are important problems for reinforced concrete structures, so they can be solved by low alloying of steel and the application of subsequent thermal reinforcement. Methodical furnaces are widely used in modern processing shops for rolling fittings.

The methodical furnace currently used in Baku Steel Company LLC is a three-zone thermal furnace. The temperature in the first zone is 500–1,000 °C, in the high-temperature zone 1,200–1,250 °C, and in the long-term heating zone, the temperature is 50–100 °C higher than the temperature required for treatment. The temperature of the metal coming out of the furnace is in the range of 1,250–1,350 °C for rolling, which allows the rolling process to go better.

Because, if there are any drops in the temperature of the metal coming out of the furnace, it definitely manifests itself during rolling, i.e. the degree of deformation between the shafts increases. This has a negative impact on the regulation of the required dimensions. The metal from the furnace is deformed on a three-shaft (trio) rolling machine and formed in the final output caliber 70×70 mm, then enters the draft box, the beginning and end of the 32–34 mm circular metal paste passing through the square-oval-rhombus-circular transitions are cut. At the next measurement completion area, the profile is measured according to the profile size of the pulling armature by opening the side loop on the tension shafts, and then the paste enters the calibration zone.

Thus, depending on the profiles in the rolling area, fittings are produced by passing through 12–15 rolling machines. Two technologies are used in the production of reinforcing steels: hot-rolled and thermomechanical rolling according to the zone of thermal impact. High plasticity in hot-rolled fittings has a negative effect on many properties, including their rapid wear and corrosion, as well as early equipment failure [17, 18].

Fig. 1 shows the shape and profile of the fittings produced by Baku Steel Company LLC.

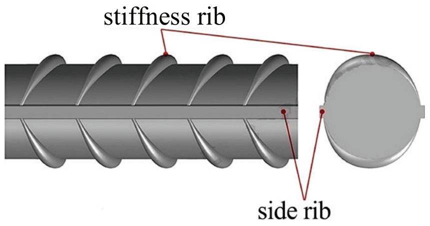

Fig. 1. Shape and profile of construction fittings

It should be noted that the fittings of different sizes purchased at the plant have quite strong stiffness ribs. Fig. 2 shows a tensile diagram to assess the mechanical properties of the fittings produced.

It can be seen from the deformation diagram that reinforcing steels smelted in an electric arc furnace from metal waste with the addition of metalized NVG pellets have fairly high ratios of yield strength and strength R_t/R_m. This factor is direct evidence of high bearing capacity while maintaining high ductility and, consequently, fairly good weldability of reinforcing steel.

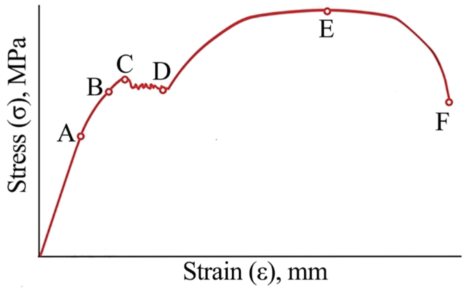

Fig. 2. Tensile diagram of construction reinforcing steel: A — proportion limit; B — elasticity limit; C — maximum yield strength; D — minimum yield strength; E — tensile strength limit; F — fracture strength (creation of the necklace)

5. 3. Thermal reinforcement is the most effective technology to increase the strength properties of carbon steels

Thus, after the rolling operation is completed, the steel is rapidly cooled directly from the austenite state, resulting in a low-temperature decomposition structure of austenite, unlike ordinary steel. Fig. 3 shows a diagram of the transformation of austenite in reinforcing steel depending on temperature regimes.

During thermal hardening, the decomposition temperature of austenite drops, resulting in a slight delay in the separation of extreme ferrite and the formation of dispersed perlite (sometimes bainite). Here, a small thickness of martensite structure can be obtained on the surface of steel plates, but since the initial temperature of martensite conversion (σ_b=400–450 °C, 0.2 % C) is high in these steels, the resulting martensite structure is self-leveling due to heat in the plate [19, 20].

In other words, the surface temperature of the rapidly cooled plates is then equalized by the heat in the inner layers, and the resulting reinforced structure is self-leveling. No additional stratification is required for such fittings.

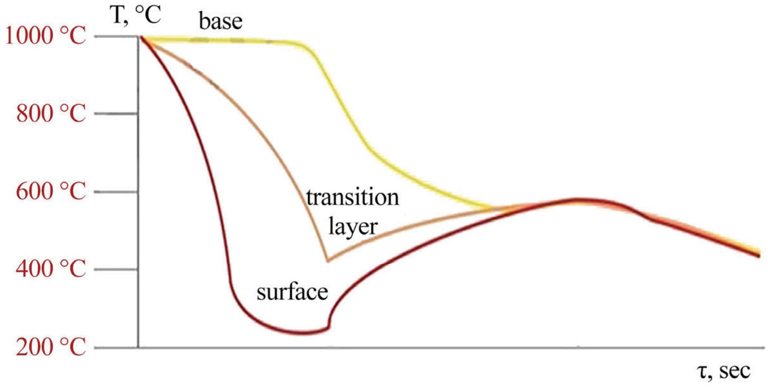

Fig. 3. Diagram of the transformation of austenite depending on temperature regimes

5. 4. Structural transformations during thermomechanical hardening

As noted, the thinning of only a thin surface layer of steels during thermal hardening is explained by the low stability of the supercooled austenite and the high rate of crushing of the coating (500–1,000 °C/sec.).

Fig. 4 shows a diagram of the transformations that occur in steel during the spreading of reinforcing steel.

The free ferrite obtained during thermal hardening is distributed around and inside the grains in the form of thin layers in the shape of needles. Such a structure increases the mechanical properties by 1.3–1.5 times and reduces the occurrence of cooling, and saves 15–60 % of metal in construction work, increasing the reliability of welded structures. The inlet temperature of the armature is 980–1,080 °C, and in the outlet zone, it is 580–650 °C depending on its mechanical properties [21, 22].

The length of the tempo is 3,920 mm in zone 1, 4,200 mm in zone 2, and 5,200 mm in zone 3. Its total length is 13,320 mm. The length of the thermal furnace together with the working zone is 21,000 mm. After heat treatment, the structure of the armature consists mainly of martensite and sorbitol-troostite. This part is surrounded by an area 2–3 mm thick in the structure in Fig. 5 below.

Fig. 6 shows the 500-fold magnification of the unvaccinated and welded microstructure of low-carbon reinforced steel subjected to high-temperature thermomechanical treatment. Examination of these microstructures shows that the microstructure of the armature consists of troosto-sorbitol. Such a structure is obtained only after tabulation in high-temperature thermomechanical treatment and high-temperature (580–620 °C) stratification due to the heat of the spread.

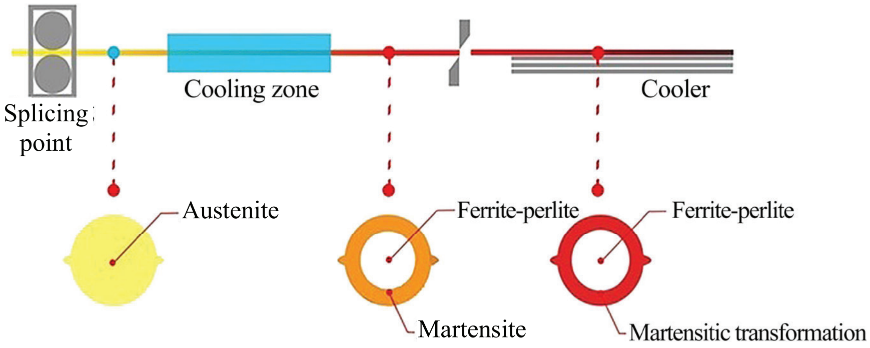

Fig. 4. Scheme of transformations that occur in steel during the production of fittings according to the technological scheme

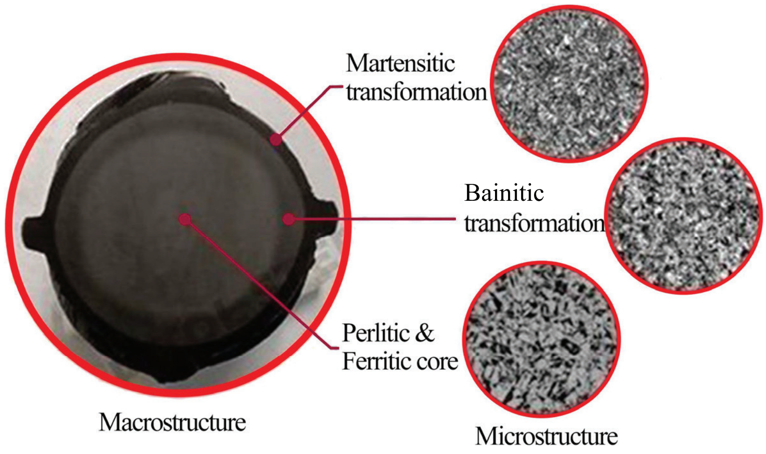

Fig. 5. Structural transformations of the armature after heat treatment

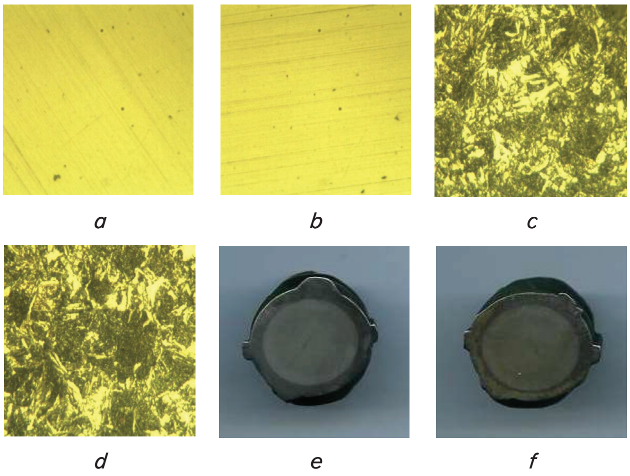

Fig. 6. Microstructure of Ø20 armature ×500: *a, b* — unvaccinated, not etched; *c, d* — vaccinated, etched samples; *e, f* — structure of the thermal zone; *a, c* — steel microstructure before thermal hardening; *b, d* — steel microstructure after thermal hardening

As a result of our research, it was determined that the effect of high-temperature thermomechanical treatment on the cooling rate, which can provide the structure of martensite in low-carbon low-alloy steels, is observed when the final rolling temperature is up to 1,070 °C. As this temperature decreases, the effect of HTMT increases.

On the other hand, reducing the pause between the end of the roll and the onset of intense cooling increases the effect of high-temperature thermomechanical treatment. The degree and rate of deformation also have a significant effect on the treatment effect [23, 24].

One of the important factors in the strengthening of carbon steel during heat treatment is the intensive cooling of the steel at the outlet of the rolling mill. In this case, special attention must be paid to the fact that the fittings are cooled both in cross-section and length. In many cases, ensuring equal cooling allows to prevent residual deformation of the product and reduce residual stresses.

6. Discussion of the results of the study of structural transformations and properties of reinforcing steel

Rebar steel melted in an electric arc furnace from metal waste using metalized pellet HBI has a composition corresponding to the chemical composition of low-carbon low-alloy steel. Such steel has a stable chemical composition on different melts and is almost depleted of harmful non-metallic inclusions (Table 1). Continuously cast blanks from it have a finely dispersed microstructure consisting of ferrite and perlite (Fig. 6, *a*, *c*). Such a structure is well subjected to rolling with subsequent heat treatment. The advantage of this steel in the cast state is the use of a small amount of metalized pellet (up to 20 % of the total mass of the charge), which increases the efficiency of melting the charge in the electric arc furnace and the deoxidation process of the steel.

With high-temperature thermomechanical treatment (rolling+hardening+high tempering), steel is hardened on the basis of a dislocation mechanism. At the same time, in the process of deformation in the structure of steel, double austenite occurs. Consequently, such a strongly deformed austenite has a high instability and, when cooled in air, turns into martensite. Long-range cooling of workpieces in air leads to high-temperature release, the result of which is the release of dispersed phases from martensite having a high density of dislocations. It is the dispersed phases that are the initiators of the hardening of steel, without impairing its weldability.

Therefore, steels undergoing high-temperature thermomechanical treatment have a high strength at the level of 1,000 MPa, with a requirement of 500 MPa, i.e. in strength 2 times exceeds the established norm of the European standard. However, large-scale production limits the possibility of managing the structure formation of the various batches of steel produced due to the heterogeneity of charge materials, and consequently the production of stable properties. To eliminate this drawback, it is necessary to improve the technology for selecting charge materials for the smelting of reinforcing steels, which provides a stable chemical composition, and hence a uniform structure of the reinforcement.

Further development of the processes of structure formation of reinforcing steels is associated with the study of transformations at the level of nanoparticles and clusters. It is necessary to study the state and structure of the structural phases obtained as a result of precipitation hardening of steel.

7. Conclusions

1. The use of low-carbon or low-carbon alloy steels is more effective in the production of structural reinforcing steels to ensure high technology and welding capacity of the reinforcement.
2. The application of the high-temperature thermomechanical treatment process in the production of fittings from low-carbon and low-carbon low-alloy steels is more effective. In this case, it is possible to increase the flow rate of steel up to 1,000 MPa. In construction, this requirement is 500 MPa, i.e. it is possible to exceed this figure twice.
3. The advantage of annealing due to the rolling temperature is the use of rolling heat without reheating the armature steel. This saves energy (fuel) needed to reheat steel.
4. Twinning of austenite during high-temperature deformation in the structure leads to an increase in its metastability, as a result of which the steel is strengthened after hardening due to precipitation hardening during high-temperature tempering.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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References

1. Aslanov, T. İ. (2002). Metallar texnologiyasının əsasları və tikintidə qaynaq işləri. Bakı: “Təhsil” NPM, 528.
2. Kərimov, R. İ., Hüseynov, M. Ç., Quliyev, F. T., Həmidova, Ə. İ. (2017). Azkarbonlu və azlegirlənmiş karbonlu poladların sulfid daxilolmaların deformasiyası və onlara yayama temperaturunun təsirinin tədqiqi. Metallurgiya və materialşünaslığın prob-lemləri” mövzusunda 2-ci Beynəlxalq Elmi-texniki konfransın materialları. Bakı, 34–36.
3. Mustafazade, F. M. (1998). Tekhnologiya materialov. Baku: AzISU, 386.
4. Malysheva, B. D. (Ed.) (1977). Svarka i rezka v promyshlennom straitel’stve. Moscow: Stratizdat, 780.
5. Mammadov, A., Ismailov, N., Huseynov, M., Guliev, F. (2022). Structural changes in thermal hardening of construction reinforcing steels. Report in XII International scientific-practical conference “Comprehensive ensuring quality of technological processes and systems”. Vol. 2. Chernihiv, 18–20. Available at: https://drive.google.com/file/d/12lgyVlJBzsaO7WL6Y9nrYjLrDYWcMMGE/view
6. Mammadov, A., Ismailov, N., Huseynov, M., Guliev, F. (2022). Some aspects of modeling of the steel-making prosess. Report in XII International scientific-practical conference “Comprehensive ensuring quality of technological processes and systems”. Vol. 2. Chernihiv, 20–21. Available at: https://drive.google.com/file/d/12lgyVlJBzsaO7WL6Y9nrYjLrDYWcMMGE/view
7. Rakhmanov, S. R., Mamedov, A. T., Bespal’ko, V. N., Topolov, V. L., Azimov, A. A. (2017). Mashinostroitel’nye materialy. Spravochnye dannye, terminy i opredeleniya. Dnepropetrovsk-Baku: «Sabakh», 410.
8. Rakhmanov, S. R., Topolov, V. L., Gasik, M. I., Mamedov, A. T., Azimov, A. A. (2017). Protsessy i mashiny elektrometallurgicheskogo proizvodstva. Baku-Dnepr: «Sistemnye tekhnologii» - izd. «Sabakh», 568.
9. GOST 3402-2016. Prokat armaturniy dlya zhelezobetonnykh konstruktsiy. Tekhnicheskie usloviya.
10. GOST 52544-2006. Prokat armaturniy svarivaemiy periodicheskogo profilya. Tekhnicheskie usloviya.
11. EN 10080:2005. Stal’ dlya armirovaniya zhelezobetonnykh konstruktsiy. Tekhnicheskie usloviya.
12. ASTM A615 M / ASME SA615 M. Reglament dlya deformirovannykh i gladkikh sterzhney iz uglerodistoy stali s opredelennoy dlinoy dlya armirovaniya betona.

13. Məmmədov, A. T., İsmayılov, N. Ş., İmanova, R. A., Bayramova, F. İ. (2017). “Baku Steel Company” MMC – də mövcud texnoloji proseslərin təhlili. AzTU – nun elmi əsərləri, 2, 75–79.
14. Fralov, Ya. V., Rakhmanov, S. R., Babanly, M. B., Karimov, R. I., Mammadov, A. T. (2022). Technological processes and mills of cold pilcer pipc Rolling. Dnepr-Baku: “Sabah”, 276.
15. Şərifov, Z. Z., Məmmədov, A. T., Əliyev, Ç. M. (2019). Qaynaq texnologiyası və avadanlığı. Bakı, 306.
16. Velichko, A. G., Rakhmanov, S. R., Babanly, M. B., Mamedov, A. T., Bayramov, A. T. (2021). Vnepechnaya obrabotka pri proizvodstve vysokokachestvennykh staley. Baku, 467.
17. Mamedov, A. T., Ismailov, N. Sh., Guseinov, M. Ch., Guliev, F. T. (2022). Criteria for selecting a method of out-of-furnace treatment steel for the oil and gas industry. Materialy mezhdunarodnoy nauchno-prakticheskoy konferentsii «Mashiny, agregaty i protsessy, proektirovanie, sozdanie i modernizatsiya». Sankt-Peterburg, 48–50. Available at: https://www.elibrary.ru/item.asp?id=47995757
18. Oborudovanie i tekhnologiya termicheskoy obrabotka metallov m splavov v mashinostroenii. Ch. 1. Sb. Dokladov II mezhdunarodnogo simpoziuma (2001). Kharkiv: IPU “kontrast”, 196.
19. Rakhmanov, S. R., Mamedov, A. T. et. al. (2021). Osnovy tekhnicheskoy ekspluatatsii metallurgicheskogo oborudovaniya. Vol. 1, Ch. 1. Nadezhnost’ i ekspluatatsiya uzlov metallurgicheskikh mashin. Baku-Dnepr, 588.
20. Rakhmanov, S. R., Mamedov, A. T. et. al. (2021). Osnovy tekhnicheskoy ekspluatatsii metallurgicheskogo oborudovaniya. Vol. 2, Ch. 2. Ustroystvo i ekspluatatsiya gruzopodemnykh metallurgicheskikh mashin i oborudovaniya aglomeratsionnykh fabrik i koksokhimicheskikh tsekhov. Baku-Dnepr.
21. Rakhmanov, S. R., Harmashov, D. Yu., Medvediev, M. I., Balakin, V. F., Mamedov, A. T., Azimov, A. A. (2021). Pat. No. 148969 UA. Sposib presuvannia trub. No. u202101943; declareted: 13.04.2021; published: 05.10.2021, Bul. No. 40. Available at: https://base.uipv.org/searchINV/search.php?action=viewdetails&IdClaim=278393
22. Kerimov, R. I. (2019). Improving steel melting intensity in the process of electrosmelting from waste and pellets (HBI). Eastern-European Journal of Enterprise Technologies, 3 (1 (99)), 35–42. doi: https://doi.org/10.15587/1729-4061.2019.168352
23. Karimov, R. İ. (2020). Features of removal of Phosphorus and sulfur from Remlturing stock turing electric arc melting of Steel. International journal of Control and Automation, 13 (1), 137–159.
24. Karimov, R. İ. (2020). Thermodynamic features of increasing the efficiency of metallurgical processes during electric steel melting. Rensta San Gregorio Ecuador, 2, 845–864.